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Response of the Great Barrier Reef to sea level and environmental changes over the past 30,000 years

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Previous drilling through submerged fossil coral reefs has greatly improved our understanding of the general pattern of sea-level change since the Last Glacial Maximum (LGM), however, how reefs responded to these changes remains uncertain. Here we document the evolution of the Great Barrier Reef (GBR), the world's largest reef system, to major, abrupt environmental changes over the past 30 ka based on comprehensive sedimentologic, biologic and geochronologic records from fossil reef cores. We show that reefs migrated seaward as sea-level fell to its lowest level during the last glaciation (~20.5-20.7 ka), then landward as the shelf flooded and ocean temperatures increased during the subsequent deglacial (~20-10 ka). Growth was interrupted by five reef death events, caused by subaerial exposure or sea-level rise outpacing reef growth. Around 10 ka the reef drowned as the sea level continued to rise, flooding more of the shelf, and causing higher sediment flux. The GBR's capacity for rapid lateral migration at rates of 0.2-1.5 m yr^{-1} — and the ability to recruit locally — suggest that, as an ecosystem, the GBR has been more resilient to past sea-level and temperature fluctuations than previously thought, but it has been highly sensitive to increased sediment input over centennial-millennial timescales.

The LGM and subsequent deglaciation represents a major re-organization of the global climate system, with rapid sea-level rises (e.g., meltwater pulses: MWP-1A0, 1A, 1B, 1C)[1-4] linked to ice sheet collapse, changes in global ocean circulation and temperatures[5], and periods of divergent atmospheric CO_2 concentrations and ocean aragonite/calcite saturation states[6]. Although understanding responses of coral reef systems to these major, abrupt environmental changes is crucial for placing possible reef futures into an appropriate time frame within the context of global processes[7,8], few fossil reef records (e.g., Barbados, Huon Peninsula, Vanuatu, Tahiti)[1,2,9-11] fully span this ~30-10 kyr period. Thus, questions remain about the critical environmental thresholds that led to reef demise[9,12] in the past and how reefs recover following disturbances on different spatio-temporal scales[13-15].

In this study we present a synthesis of all available geomorphic, sedimentologic, biologic and dating information from fossil reef cores recovered from the GBR shelf edge reefs during Integrated Ocean Drilling Program (IODP) Expedition 325[16]. Radiometric and geochemical investigations of these cores, combined with sediment cores from the adjacent basin, have yielded precise constraints on variations in relative sea level[17], sea surface temperature (SST)[18] and sediment flux[19] over this period. We now document how the GBR responded to these major environmental variations, including corresponding changes to reef morphologies, communities, and growth rates. We also confirm the existence and location of reef refugia[20,21] during the LGM sea level and establish the critical environmental conditions at which the reef died and re-established on centennial-millennial timescales[8] over the past 30 ka.

Shelf edge reef structure, composition and sequences

Transects of reef cores were recovered off Mackay (Hydrographer's Passage at 19.7^{o}S; HYD-01C; Sites M0030-39) and Cairns (Noggin Pass at 17.1^{o}S; NOG-01B; Sites M0053-57), consisting of twenty holes drilled at sixteen different sites (Figs. 1, 2; Supplementary Notes 1-2), and were used to investigate the evolution of the GBR. U/Th and ^{14}C AMS dating[16-18,22] of >580 corals and coralline algae, combined with sedimentologic and biologic analyses (Methods), provide a robust chronostratigraphic framework for assessing the impacts of abrupt sea-level and associated environmental changes (Supplementary Notes 2-5; Supplementary Figs. 1-2). First, we show that the GBR had a complex and dynamic history of reef growth and demise over the past 30 ka, characterized by five distinct reef sequences (Reefs 1–5) that recorded episodic seaward (offlapping) then landward (onlapping) reef growth across the shelf (Figs. 1-2). Each reef sequence consists of coherent, coeval shallow and deep reef habitats that can be traced in time and space. Second, we establish the nature and timing of the reef initiation and demise events, while documenting the corresponding changes in coral-algal assemblages, vertical accretion rates (i.e., upward growth of the reef), and paleoenvironmental conditions at each stage of the GBR's development.

The development of the five reef sequences over the past ~30 ka reflects the GBR's responses to major changes in global climate (Fig. 3a). As temperatures cooled into the LGM, high latitude ice sheets reached their maximum extent, reducing global mean sea levels (GMSL ~125-130 mbsl)[17]. In the GBR, relative sea level (RSL) was lowest (~118 m) by ~20.7-20.5 ka[17] (Fig. 3b,d). Western Pacific SST's also were lowest at 18-20 ka[18,23] (Fig. 3a), with a corresponding much larger north-south SST gradient pointing to a northward expansion of cooler subtropical waters and changes to GBR ocean currents[18]. As the deglaciation progressed from the LGM to 10 ka, SST's warmed and sea level rose, albeit rapidly and non-linearly, as a result of global ice sheet melting (Fig. 3a)[17]. Sea-level change over the LGM to deglacial period was the primary, though not the sole driver, of spatio-temporal variations in reef development, coral-algal assemblages and vertical accretion rates, as recorded in the five reef sequences (Fig. 3-4). Below we explore the interplay between the major environmental drivers (sea level, SST, sediments) at each stage of the GBR's development and demonstrate that its growth and demise has been more complex than previously thought[20,21].

Reef growth and demise during global glaciation (27-22 ka)

The GBR initiated growth on the shelf edge at 28–27 ka following the GMSL fall[24] from Marine Isotope Stage (MIS) 3 to MIS 2. At Noggin Pass an age of 35.6$\pm$0.30 to 34.3$\pm$0.30 ka[22] (core M0056A-2R) constrain the timing of exposure and death of Reef 1 (Supplementary Note 2) as GMSL fell ~40 m[24] at the inception of the LGM. The oldest ages from the inner terraces (holes M0031-33A, 55A) indicate that Reef 2 started growing on MIS3 or older slope deposits between 27.35$\pm$0.14 to 27.34$\pm$0.07 ka — synchronously across the two regions as shallow-water reef growth migrated seaward. At this time the GBR formed a very narrow and ephemeral fringing reef system[25], that was capable only of slow vertical growth (0.3-2.5 mm yr^{-1}) compared with adjacent, modern Holocene counter-parts (Reef 5) (Fig. 3b, d, Supplementary Figs. 3, 4). These apparently poor reef growth conditions are consistent with globally synchronous slow vertical accretion rates (see meta-analysis, Supplementary Figs. 5, 6) but the reasons remain unclear (e.g., restricted accommodation space, higher local sedimentation during sea level fall)[26].

While the timing and maximum extent of the LGM remain controversial[24], RSL in the GBR fell to ~118 m below present by 20.70$\pm$0.20 to 20.51$\pm$0.02 ka[17]. Major growth hiatuses at ~105 mbsl, at both transects (holes M0055A, 31-33A), represent the turn-off of Reef 2 at 22.11$\pm$0.23 to 21.87$\pm$0.24 ka. Coral-algal assemblages indicate paleowater depths were shallow (<10 m) before Reef 2 death, and lithologic, diagenetic and seismic evidence[16,17,22,25] confirms the top of the reef is a subaerial exposure surface, consistent with a major RSL fall (Methods and Supplementary Note 2). However, shallow reef development migrated ~0.4 to 3 km seaward in <2 kyr, indicating a robust GBR ecosystem during the LGM capable of average reef habitat migration rates of 1.5 and 0.2 m yr^{-1} at Hydrographer's and Noggin, respectively.

Ice age reef refugia - surviving and thriving during the LGM (21-19 ka)

These are the first direct data showing reefs established on the GBR shelf edge during the LGM sea level, and demonstrate that recruitment by propagules from external reef refugia (e.g., Queensland Plateau)[21] was not necessary for the GBR to survive harsh LGM conditions. At both locations, Reef 3a initiated growth at 20.70$\pm$0.20 to 20.51$\pm$0.02 ka on top of deeper, forereef slope deposits of Reef 2 (Fig. 1-2) at the base of the mid-terraces (holes M0036A, 35A, 39A and 53A), indicating a pattern of shallowing, offlapping sequences related to seaward migration of the GBR. Shallow coral-algal assemblages (<10 m) dominate the LGM and the subsequent sea-level rise until 17 ka, leading to continuous vertical aggradation of Reef 3a at accretion rates of 3.9–4.4 mm yr^{-1}, similar to Holocene rates. While Reef 3a has no discernible reef drowning event or distinct changes in coral-algal assemblages associated with the 19 ka meltwater pulse (MWP-1A0), hole M0053A has a clear inflection point, indicating major slowing of accretion (3.9 to 1.8 mm yr^{-1}) after 19.22$\pm$0.01 ka.

Rapid sea-level rise, shelf flooding, reef growth, and then demise (17-13 ka)

The deglaciation (~17-16.5 ka) saw a major re-organization of GBR shelf edge reefs from aggrading to onlapping, shallow sequences. Continued and rapid sea-level rise and associated environmental changes (e.g., sediment flux) had two main impacts: (1) re-flooding and re-initiation of reef growth on the inner terraces (holes M0033-31A, 55A); and (2) major changes in lithologies, assemblages, accretion rates and ultimately reef drowning on the most distal part of the shelf edge (mid, outer terraces) (holes M0035A, 36A, 39A, 53A, 54A,B). Inner terrace ages tightly constrain re-flooding of the dead Reef 2 and the turn-on of Reef 3b at 16.85±0.24 to 16.24±0.24 ka. This represents a landward migration of shallow-water coral-algal assemblages from outer and mid terraces to the inner terraces that coincided with a major environmental perturbation causing drowning of Reef 3a. Down-hole gamma ray logs[16] from the inner and mid terraces at Hydrographer's (holes M0031A, 36A) (Supplementary Figs. 1-2) indicate an increased flux of fine terrigenous sediments ~16 ka on the now deeper, fore-reef slope that may have reduced light availability and water quality, causing Reef 3a drowning. This is consistent with shelf flooding reconstructions showing a peak in the area of flooded shelf at Hydrographer's at ~16 ka (Supplementary Note 5).

Meanwhile, on the inner terrace (holes M0031-33A, 55A), active fringing reef growth continued, even flourishing at Hydrographer's, with vertical accretion rates up to 20 mm yr^{-1} at 15.5–15.0 ka. These rates, the highest recorded from the GBR (Fig. 3) for the past 30 ka, coincided with a shift to shallow, high energy, reef habitats characterized by a mix of coral assemblages (dominated by *Isopora, Acropora* or *Seriatopora*). At this location, in spite of the high sediment flux indicated by the gamma ray data, Reef 3b kept pace with the rapid rises in sea-level and SST[18,23] prior to MWP1A. Studies of Holocene near-shore reefs in the GBR indicate that even the most turbid fringing reefs are capable of vertical accretion rates that match or exceed those of clear water, outer shelf reefs[27,28]. Unlike the mid and outer terraces, the nearshore Reef 3b was less sensitive to sediment flux, and grew rapidly as accommodation increased with rapidly rising sea levels.

While the exact timing differs, our meta-analysis of Barbados and Tahiti data (Supplementary Figs. 5, 6) shows the highest accretion rates in both records clustering around the disputed[1,2] timing of MWP1A. Results from Tahiti provide firm constraints on the timing (14.65-14.31 ka) and magnitude (14-18 m) of MWP-1A[2] and confirm that the Tahiti reef did not drown then[9]. The GBR record also shows no distinct drowning event directly correlated with MWP-1A, and the continuous shallow-water assemblages (<10 m) throughout some cores (M0031-33A), and the lack of recovery in others (M0055A), make it impossible to improve the Tahiti MWP-1A constraints[17]. Ultimately, however, the sustained, rapid sea level rise during MWP1A[2] and prior to the Younger Dryas (YD)[17], combined with declining oceanographic conditions[26], contributed to the final demise of Reef 3b at 13.72$\pm$0.07 ka.

Fringing to barrier reef transition and birth of the proto-GBR (13 ka)

Rapid deglacial sea-level rise[17] forced a major landward migration of shallow reef habitats 1.3–1.8 km to the inner (Noggin, hole M0057A) and outer barrier (Hydrographer's, hole M0034A) in <2 kyr. Reef 4 initiated growth soon after reflooding of Reef 1 between 73 and 64 mbsl at 13.09$\pm$0.08 and 12.97$\pm$0.07 ka[17] for Hydrographer's and Noggin, respectively. Reef 4 exhibits mainly continuous, shallow-water (<5-10 m) *Isopora*-dominated assemblages with very rapid initial accretion rates up to 9.6 mm yr^{-1} (Fig. 3). The Tahiti, Vanuatu, and Huon Peninsula records have similarly rapid accretion rates (8–12 mm yr^{-1}) during the YD (Suppl. Figs. 5, 6). This rapid growth probably reflects the dominance of *Acropora*-*Isopora* reef frameworks and coincides with West Pacific SST reaching modern values[18,23]. For the GBR, this also represents a major reorganization from fringing to barrier reef-dominated morphologies (Figs. 1, 2) that can be traced almost continuously over 2,000 km[25], and represents the true “proto-GBR” that preceded the modern Holocene barrier reef. Basement substrate highs beneath the barriers[25] may have influenced this morphologic change, and similar fringing to barrier transitions are observed in Tahiti as the developing barrier acted to initially trap sediments promoting rapid reef growth[29].

Demise of the proto-GBR caused by massive sediment flux (10 ka)

The top of Reef 4 is marked by slower accretion (4.2 and 1.4 mm yr^{-1}; at Hydrographer’s and Noggin, respectively) as the sequence transitioned to deeper assemblages at 10.32$\pm$0.04 to 10.14$\pm$0.16 ka — well after the 11.45 ka MWP-1B at Barbados[1,3,30]. The GBR data are consistent with Papeete[31] and Expedition 310 data[9] and show no evidence for an abrupt drowning event directly associated with the 14$\pm$2 m sea-level pulse at ~11.45 ka. The question remains as to what caused this period of slower accretion and sub-optimal conditions that prevented keep-up growth, and led to the final drowning of the “proto-GBR” at 10.31–10.14 ka. Sediment cores along a 2700 km north-south GBR transect show a massive increase in the flux of fine siliciclastic and carbonate sediments to the slope between 11 and 8 ka, peaking at ~10 ka, and almost three times above LGM to Holocene background levels[19,32]. This is consistent with shelf flooding models showing >60–75% of the shelf area inundated around this time (Fig. 3b,d Supplementary Note 5). While the impact of higher pCO_2 (>260 ppm) and reduced reef calcification[33] cannot be ruled out, we propose that Reef 4 drowned as a direct consequence of this elevated sediment flux and reduced water quality reaching a threshold level, against a backdrop of continued sea-level rise. This interpretation is consistent with declining vertical accretion rates prior to final drowning as the barrier building, but highly sediment intolerant[34], *Isopora*-dominated community became stressed and eventually gave up[29,35]. However, this remains to be tested against other indicators of sediment stress (ie. increased bioerosion). The final landward reef migration and GBR-wide turn-on of the modern Holocene GBR (Reef 5) at ~9 ka[20] occurred as sea levels rose above the Last Interglacial (125 ka)[21,22] reef substrate at ~10–20 mbsl.

Implications for understanding GBR demise and resilience

IODP Expedition 325 provides the first continuous record of the GBR's evolution over the past 30 ka (Fig. 4). Patterns of growth and demise of the five reefs are consistent between the two locations, although some differences in reef architecture and composition reflect local variations in shelf geometry, substrate, sediment flux and SST gradients. Sea-level change was the fundamental control on reef development and position as the GBR closely tracked falling and rising sea-levels across the shelf edge. At times the reef was able to track rising sea-level, accreting vertically at up to 20 m kyr^{-1} and migrating laterally at 1.5 m yr^{-1}. Reef death occurred in two ways: subaerial exposure caused by sea-level fall; or reef drowning due to rapid sea-level rise and associated environmental changes (Supplementary Table 6). Unlike previous studies[1,12,35], our findings highlight the importance of high sediment flux and poor water quality, rather than abrupt sea-level rise alone (i.e., MWPs), in ultimately determining reef demise. We also show that reef morphology (fringing vs. barrier), reef location (shelf distal vs. proximal), and coral assemblage composition (e.g., *Isopora*-dominated) also influenced sensitivity of the GBR to past sediment fluxes.

The GBR persisted on the shelf edge throughout the LGM and, where suitable substrates were available, shallow-water reef habitats were capable of migrating seawards and then landwards in response to sea-level and other environmental changes. This temporal continuity of reef habitats within the GBR also provided a potential source of coral-algal recruits for re-establishing reefs locally, without requiring external or regional refugia[21]. We attribute the GBR's robustness on centennial-millennial scales, despite such major environmental perturbations as rising sea levels (~120 m, up to 30 mm/yr)[17] and temperatures (~3-4 ^{o}C over the deglacial, up to 0.04 ^{o}C/100 yrs)[18], to the presence of adjacent coeval shallow and deep reef habitats that provided the recruits (particularly broadcast-spawners) that enabled rapid migration across the shelf and persistence of ecosystem connectivity similar to modern reef systems[36]. This hypothesis may explain (in part) how the GBR has reconstituted again and again on 100-kyr times scales over its longer term history[15]. Finally, our findings demonstrating the GBR's sensitivity to such environmental factors as sediment flux and water quality over centuries to millennia, are consistent with declines on some inshore GBR reefs over the past two centuries since European settlement[13]. However, given the current rate of SST increase (0.7 ^{o}C/100 yrs), sharp declines in coral coverage[37], and the potential for year-on-year mass coral bleaching[38], our new findings provide little evidence for resilience of the GBR over the next few decades.

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Author contributions

J.M.W. and Y.Y. were co-chief scientists of Expedition 325 J.M.W. wrote the manuscript in collaboration with J.C.B, M.H, D.C.P, Y.I, R.B, T.E, Y.Y, H.M and the paper was refined by contributions from the rest of the co-authors.

Competing financial interests

The authors declare no competing financial interests.

Figure captions

Fig. 1. Geomorphic, chronostratigraphic and biologic development of the Hydrographer's Passage drill transect (HYD-01C) off Mackay. **a**, High-resolution multibeam image showing the surface geomorphic context[16,39] of HYD-01C and drill hole locations (red sticks represent penetration depths). **b**, Simplified stratigraphic section showing the distribution of recovered core intervals, coral assemblages and their interpreted paleowaters depths, and selected U-Th and ^{14}C AMS ages[16,17]. Chronostratigraphic boundaries of the four main shallow reef sequences (Reefs 1-4) are represented by solid coloured lines and long dashes; short dashes show their corresponding deep-water fore-reef slope deposits (see Methods, Supplementary Notes 1-3 and Supplementary Fig. 1). Reef 5 represents the modern, Holocene reef and is characterised by deep-water fore-reef slope deposits on the shelf edge. The X-axis represents the distance across the shelf and is schematic, see panel a for actual core locations.

Fig. 2. Geomorphic, chronostratigraphic and biologic development of the Noggin Pass drill transect (NOG-01B) off Cairns. **a**, High-resolution multibeam image showing the surface geomorphic

context[16,39] of NOG-01B and drill hole locations (red sticks represent penetration depths). **b**, Simplified stratigraphic section showing the distribution of recovered core intervals, coral assemblages and their interpreted paleowaters depths, and selected U-Th and ^{14}C AMS ages[16,17]. Chronostratigraphic boundaries of the four main shallow reef sequences (Reefs 1-4) are represented by solid coloured lines and long dashes; short dashes show their corresponding deep-water fore-reef slope deposits (see Methods, Supplementary Notes 1-3 and Supplementary Fig. 1). Reef 5 represents the modern, Holocene reef and is characterised by deep-water fore-reef slope deposits on the shelf edge. The X-axis represents the distance across the shelf and is schematic, see panel a for actual core locations.

Fig. 3. Evolution of the GBR over the past 30 ka in relation to major sea-level and environmental changes. **a**, NGRIP ice core $\delta^{18}O$ record, with timing and duration of meltwater pulses (MWP-1A0 – 19 ka, MWP-1A and MWP-1B) and other global climate events (LGM, YD) as vertical grey shaded bars[1,2,17,30,31]. The brown bar shows a massive flux of fine sediment to the slope at ca. 10 ka[19] when >60-75% of GBR shelf area was flooded (Supplementary Note 4). The orange line shows Western Pacific Warm Pool (WPWP) SST anomalies (reconstructed from planktonic foraminifera Mg/Ca[23]). Points and regression lines are regional SST anomalies (Expedition 325 coral Sr/Ca[18]) from Noggin Pass (red) and Hydrographer's Passage (blue). **b** and **d**, Vertical accretion (VA) histories for HYD-01C (**b**) and NOG-01B (**d**), with the GBR maximum RSL curves[17] (blue line) and % shelf flooded (brown lines; not scaled to depth). Stepped plots are calculated vertical accretion rates, binned at 0.5 kyr intervals. **c** and **e**, Summary of spatial and temporal patterns of reef evolution (Reefs 1-5) at HYD-01C (**c**) and NOG-01B (**e**) encompassing the outer, mid and inner reef terraces, the inner and outer reef barriers and modern Holocene reef. Periods of major reef turn-on, reef turn-off or reef death events caused by reef drowning (RD) and exposure (RE), and hiatus events are shown along with the distribution of coral assemblages (same colours as in Fig. 1, 2 and 4). The grey dashed boxes represent the timing and duration of the deep-water (>10 m) fore-reef slope deposits which are sometimes coeval with shallow-water (<10 m) reef deposits upslope.

Fig. 4. Simplified model showing the evolution of the Great Barrier Reef over the past 30 ka. a, Basic chronostratigraphy, facies relationships and key stages during the development of the shelf edge reefs. Darker shading indicates the distribution of shallower (<10 m) reef facies and paler

shading deeper (>10 m). The basement substrate (orange line) is composed of MIS 3 or older deposits ranging from shallow reef (Reef 1) to deep lower shelf/slope settings. **b,** Key reef events (turn-on and reef death) and associated paleoenvironmental changes including the rate of RSL change[3], mean sea SST relative to modern[18,23] and sediment flux[19,25,26,32] (see also Supplementary Table 6).

Methods

Lithologic and chronostratigraphic analysis. The cores were logged and the stratigraphic distribution of the main reef framework (boundstones) and detrital (packstones-rudstones, unconsolidated sediments) facies defined. We used a data base of >580 published U/Th coral and ^{14}C AMS coral and coralline ages[16-18,22], combined with all available geomorphic, lithologic, coral-algal assemblage, petrophysical, and seismic information (Supplementary Notes 1-2, Fig. 7), to establish a robust, new chronostratigraphic framework for the evolution of the GBR shelf edge reef system. Four distinct reef sequences, distinguished by depth and proximity to the shelf edge, are bounded at the base by unconformities that are either subaerial exposure or maximum flooding surfaces. The top of each reef sequence records the reef death event and is bounded by either (1) the last stratigraphic appearance of shallow (<10 m paleowater depths) coral reef facies in Reefs 3a, 3b and 4 (i.e., reef drowning); or (2) a subaerial exposure surface in Reefs 1 and 2 (i.e., reef exposure). Wherever possible, the closest in-situ U/Th coral age to these boundaries was used to constrain the timing of the turn-on and turn-off of each reef sequence (Supplementary Table 6). Due to recovery issues and dating gaps, the record and cause of reef demise at ~16-17 ka and the boundary between Reef 3a and b are more tentative (long, dashed lines in Figs. 1-2; Supplementary Figs. 1-2).

Coral-algal assemblage and paleoenvironmental analysis. The lowest taxonomic level possible of all corals, and their growth positions and context were assessed in cores. Coral assemblages were identified by examining the succession of in-situ coral taxa in each hole and by using a suite of statistical analyses (cluster analysis and MDS ordination of Bray-Curtis similarities, ANOSIM, SIMPER analysis) on coral taxa and growth forms (Supplementary Note 3; Supplementary Figs. 7, 8). The coral data were then combined with coralline algal assemblage data (based on analysis of 400 thin sections) and other key indicators (percentage of coral-algal components, coralline algal crust thickness, presence/absence of vermetid gastropods measured every 10 cm) to form a coherent, internally consistent coral-algal assemblage scheme (Supplementary Table. 1). We then reconstructed the likely depositional environment (including paleowater depths) of each assemblage by comparisons with their modern GBR and other Indo-Pacific counterparts (Supplementary Note 3).

Vertical accretion analysis. Vertical accretion rates within each reef sequence were estimated using only in-situ corals and coralline algae that yielded robust U/Th and calibrated ^{14}C AMS ages[17]. Sample context was assessed using a range of established criteria[16,29], and samples from highly drill-disturbed intervals were excluded. A total of 435 samples satisfying these criteria were used to construct a robust age model and reconstruct the vertical accretion pathway for each site. To quantify the uncertainties in the age model, we used two approaches: (1) a traditional, linear visual fit and regression analysis widely used to study reef cores[2,9,31]; and (2) a Monte Carlo simulation[40]. The visual fits and regression analysis, including the rates and major inflection points, were in agreement with the Monte Carlo analysis, indicating this traditional approach accurately reflects the vertical accretion histories of the GBR (Supplementary Note 4; Supplementary Tables 3-5; Supplementary Figs. 3, 9).

Data availability. The data supporting the findings of this study are available from the corresponding author upon request.

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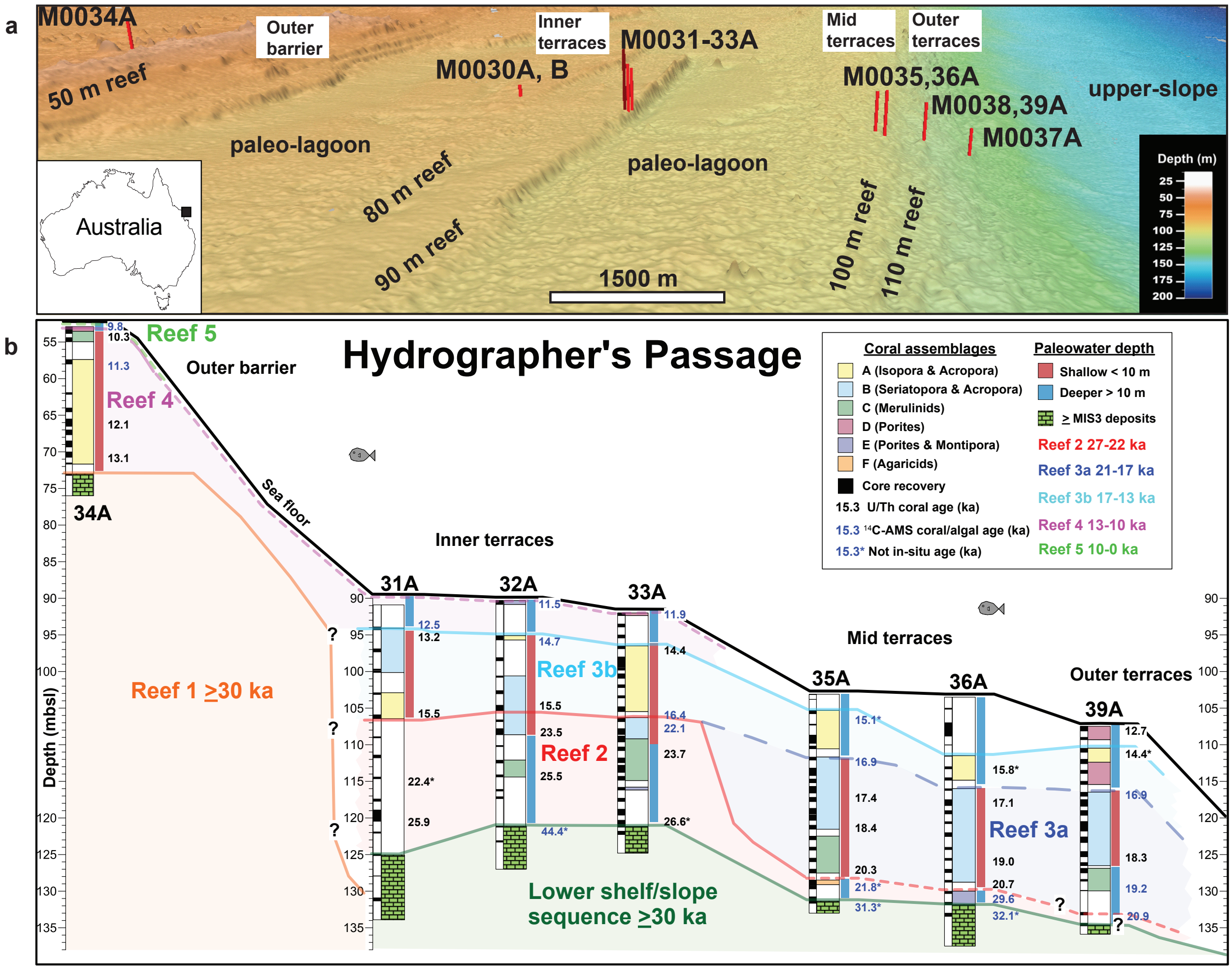
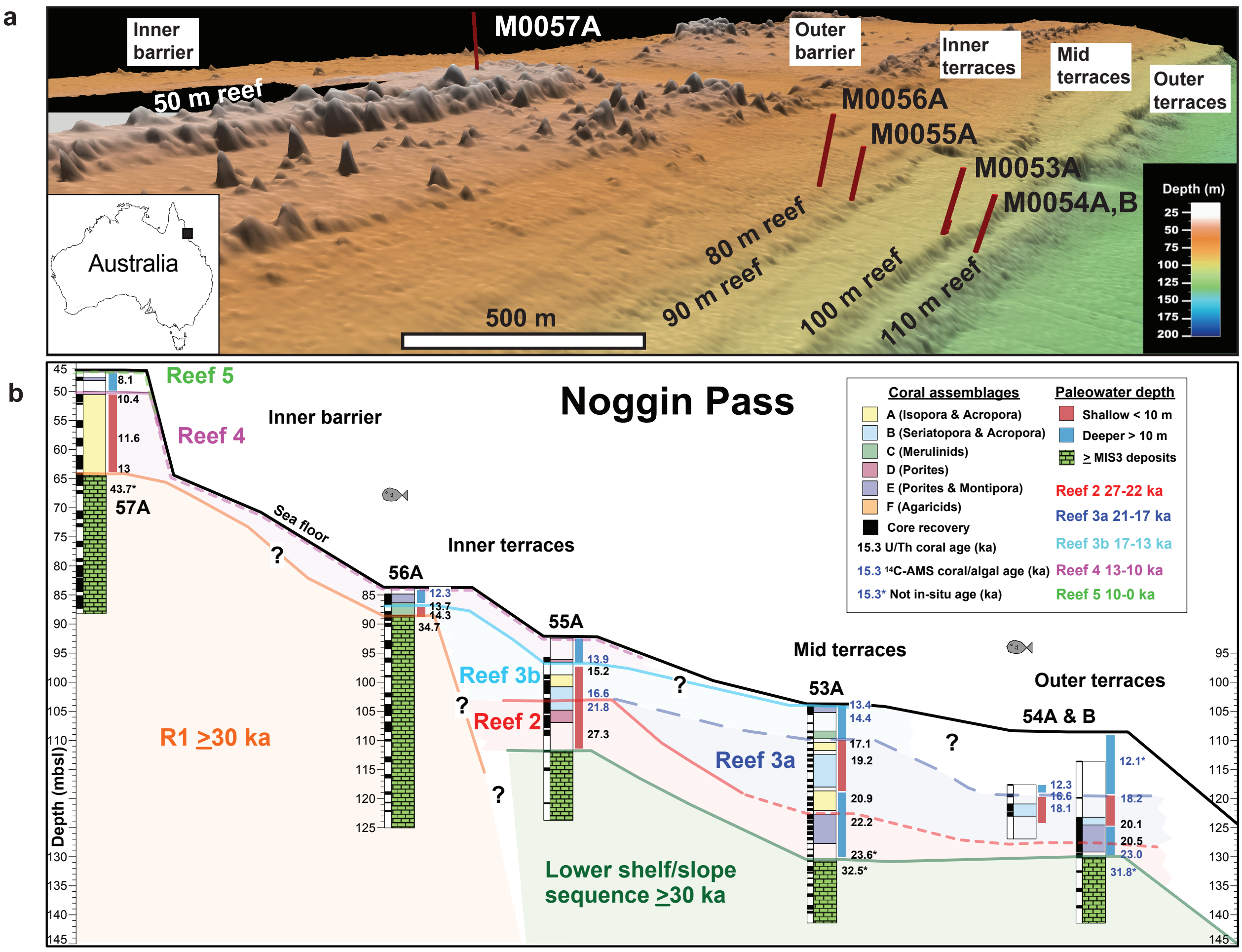
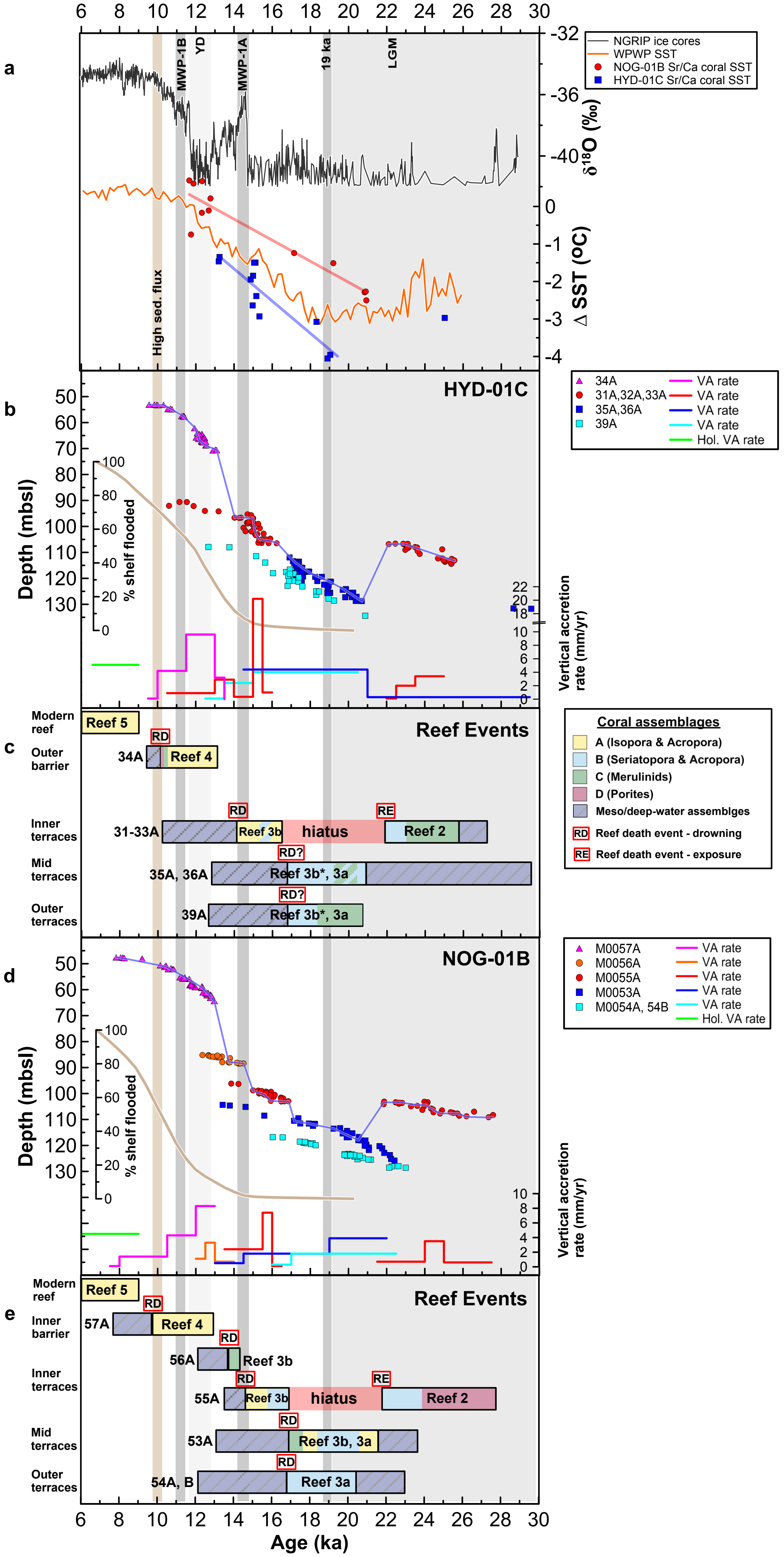
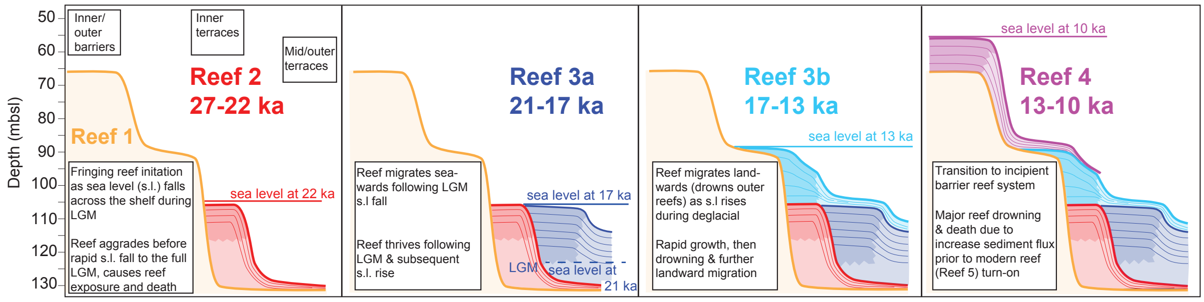

a
M0034A
Outer barrier
Inner terraces
M0031-33A
Mid terraces
Outer terraces
M0030A, B
M0035,36A
M0038,39A
M0037A
upper-slope
50 m reef
paleo-lagoon
80 m reef
90 m reef
100 m reef
110 m reef
1500 m
Australia
Depth (m)
b
Hydrographer's Passage
Reef 5
Reef 4
Outer barrier
Sea floor
Inner terraces
Reef 3b
Reef 2
Reef 1 ≥30 ka
Mid terraces
Outer terraces
Reef 3a
Lower shelf/slope sequence ≥30 ka
34A
31A
32A
33A
35A
36A
39A
Depth (mbsl)
Coral assemblages
A (Isopora & Acropora)
B (Seriatopora & Acropora)
C (Merulinids)
D (Porites)
E (Porites & Montipora)
F (Agaricids)
Core recovery
15.3 U/Th coral age (ka)
15.3 14C-AMS coral/algal age (ka)
15.3* Not in-situ age (ka)
Paleowater depth
Shallow < 10 m
Deeper > 10 m
≥ MIS3 deposits
Reef 2 27-22 ka
Reef 3a 21-17 ka
Reef 3b 17-13 ka
Reef 4 13-10 ka
Reef 5 10-0 ka


a
Inner barrier
M0057A
Outer barrier
Inner terraces
Mid terraces
Outer terraces
50 m reef
M0056A
M0055A
M0053A
M0054A,B
Depth (m)
Australia
80 m reef
90 m reef
100 m reef
110 m reef
500 m
b
Reef 5
Reef 4
Inner barrier
Noggin Pass
Sea floor
57A
56A
Inner terraces
55A
Reef 3b
Reef 2
R1 ≥30 ka
Reef 3a
Mid terraces
53A
Outer terraces
54A & B
Lower shelf/slope sequence ≥30 ka
Depth (mbsl)
Coral assemblages
A (Isopora & Acropora)
B (Seriatopora & Acropora)
C (Merulinids)
D (Porites)
E (Porites & Montipora)
F (Agaricids)
Core recovery
15.3 U/Th coral age (ka)
15.3 ¹⁴C-AMS coral/algal age (ka)
15.3* Not in-situ age (ka)
Paleowater depth
Shallow < 10 m
Deeper > 10 m
≥ MIS3 deposits
Reef 2 27-22 ka
Reef 3a 21-17 ka
Reef 3b 17-13 ka
Reef 4 13-10 ka
Reef 5 10-0 ka



a
b
c
d
e
NGRIP ice cores
WPWP SST
NOG-01B Sr/Ca coral SST
HYD-01C Sr/Ca coral SST
MWP-1B
YD
MWP-1A
19 ka
LGM
High sed. flux
δ18O (‰)
Δ SST (ºC)
HYD-01C
Depth (mbsl)
% shelf flooded
Vertical accretion rate (mm/yr)
34A
31A,32A,33A
35A,36A
39A
VA rate
Hol. VA rate
Reef Events
Modern reef
Reef 5
RD
RE
RD?
Outer barrier
34A
Reef 4
Inner terraces
31-33A
Reef 3b
hiatus
Reef 2
Mid terraces
35A, 36A
Reef 3b*, 3a
Outer terraces
39A
Coral assemblages
A (Isopora & Acropora)
B (Seriatopora & Acropora)
C (Merulinids)
D (Porites)
Meso/deep-water assemblges
RD Reef death event - drowning
RE Reef death event - exposure
NOG-01B
M0057A
M0056A
M0055A
M0053A
M0054A, 54B
Inner barrier
57A
56A
55A
53A
54A, B
Reef 3b, 3a
Reef 3a
Age (ka)

a



b

Reef	Turn-on (ka)	Turn-off (ka)	RSL (mm/yr)	ΔSST(°C)	Sediment flux	Reef death cause
Reef 1	-	≥30	↓	-	-	Sea level fall –> exposure & death
Reef 2	27	22	↓ 16-11	– -4 to -2.5	↑	Rapid sea level fall –> exposure & death
Last Glacial Maximum (lowest global sea level)						
Reef 3a	21	17	↑ 7-25	↑ -3 to -1.5	↑	Rapid level rise & high local sediment flux –> drowning & death
Reef 3b	17	14-13	↑ 27- 30	↑ -2 to -0.5	↑	Rapid level rise & increasing regional sediment flux –> drowning & death
Reef 4	13	10	↓ 4	– 0	↑	Massive regional sediment flux (3x LGM-Holocene level) & sea level rise –> drowning & death